AN RF SYSTEM FOR A 300 GeV PROTON SYNCHROTRON WITH MECHANICALLY TUNED CAVITIES

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1. INTRODUCTION

If the maximum energy of a synchrotron is increased by increasing its radius, while the acceleration time is kept constant, the required energy gain per revolution increases with the square of the machine radius. Since in addition, the RF power consumption of a given accelerating structure increases with the square of the voltage, it is obvious that the design of an RF system for a 300 GeV machine is in no way a straightforward extrapolation of existing techniques but that unusual methods may have to be used, to arrive at an efficient solution. For a typical 300 GeV machine [1] the maximum energy gain per turn amounts to 9.5 MeV and the peak accelerating voltage should be about twice this value.

Fortunately, the frequency variation buring acceleration is rather small since it is necessary anyhow to inject into the synchrotron at a rather high energy. For a 300 GeV machine the injection energy will be somewhere in the range of 3 to 10 GeV. Since these energies are nearly relativistic, one may use the approximate formula

$$\frac{\Delta f}{f} \sim \frac{1}{2\gamma_i^2}, \tag{1}$$

where $\Delta f/f$ is the frequency swing and γ_i is the total energy of the particle over its rest energy at injection. One finds $\Delta f/f = 2.9\%$ at 3 GeV and 1 % at 6 GeV.

In order to arrive at reasonable figures for the RF power consumption, one must use accelerating cavities that have much higher Q-factors than the inverse of the frequency swing. Therefore, if the conventional way of acceleration is chosen, whereby the accelerating frequency is kept synchronous with the revolution frequency, a tuning system must be employed that keeps the accelerating cavities in resonance with the varying frequency.

A mechanical tuning system has the following advantages over the conventional ferrite tuned system. Firstly, it makes it possible to choose a higher frequency — typically around 200 MHz — than ferrite materials would permit. Therefore the size of the accelerating cavities becomes smaller and the total length of accelerating structure, for a given total power loss, becomes smaller, requiring less straight section space. Secondly, since the power loss in the mechanical tuner can be made very small, the high shunt resistance of a pure copper structure can be obtained. Thirdly, it is found that the power required to drive the mechanical system can be made very small, whereas it is known that this is not the case for a ferrite system.

An objection which is frequently raised against mechanical tuning is the alleged need for very high mechanical precision. However, this objection is completely removed if the tuning is done by a selftracking servo system in the same way as is customary for ferrite cavities. This is in fact possible and in considered to be the essential feature of the proposed system. The injector for the large synchrotron might either be a linear accelerator or a «booster» synchrotron. The first possibility shall not be discussed here, but if one chooses the booster — and only the booster seems to enter into consideration for energies much above 3 GeV — one is confronted with a problem of RF acceleration that is at least as difficult to solve as that of the main ring.

Obviously, the number of pulses required from a booster of radius R_1 to fill the large ring of radius R_2 is R_2/R_1 and, in order to achieve a reasonably short filling time T, the repetition frequency of the booster must be $f_r = R_2/(R_1T)$. A typical 6 GeV booster might have R_1 — 80 m and $f_r = 25$ Hz yielding $T = 0.6$ s with $R_2 = 1200$ m. Thus, the booster is a fast cycling machine, its magnet power supply is of the resonant choke-condensor type and the time dependence of particle momentum during acceleration is a biased sinewave. It follows from this, that the required accelerating voltage is unusually large for such a small machine. For instance, a 6 GeV booster with 0.6 s filling time requires 1.7 MV per turn for a synchronous phase angle of 30° (measured from the zero-crossing of the wave).

On the other hand, the frequency swing in the booster is still rather large. A typical choice of energy for injection into the booster is 200 MeV which corresponds to a frequency swing of 1.8/1. Two alternate solutions of booster RF systems enter into consideration: ferrite cavities, as usual, or mechanically tuned cavities of the same kind as the ones proposed for the large machine itself. Although both solutions have been studied [5] in some detail and a final choice has not yet been made, the mechanical system is favoured for reasons that will be mentioned later. Only the mechanical solution will be discussed in this paper.

2. DESIGN FEATURES OF SEVRO-CONTROLLED, MECHANICALLU TUNED CAVITIES

As a result of a survey of possible methods for mechanical tuning the following design of a servo controlled electro-mechanical tuner has been chosen:

A conventional reentrant cavity is tuned by means of a capacitive tuning plunger which is located opposite the high voltage electrode of the cavity. The plunger, which has a large central aperture to let the beam pass, moves along the axis of the cavity, so as to change the width of the accelerating gap, and is driven by an electromagnetic drive system that is built exactly like the drive system of a loudspeaker. The system is shown half schematically in Fig. 1, which should be largely self explanatory. The current through the drive coil is servo-controlled by the error signal from a phase detector which measures the tuning error of the resonator. The whole cavity, including the tuner, is supposed to be part of the synchrotron vacuum chamber.

An appropriate choice of accelerating frequency or this cavity is 200 MHz (at final energy). Typical dimensions are 40 cm diameter and 50 to 60 cm length, including the tuner and its magnet. For the application in the large machine, the gap («*d*» in Fig. 1) between the plunger and the high voltage end of the resonator is about 4 to 5 cm since a very large gap voltage is required (about 130 kV peak) while the frequency swing is small. The stroke of the plunger is about 1 to 2 cm depending on the exact design and, of course, on the injection energy. For the application in the booster, the gap must be much smaller in order to cover the large frequency range. With a model cavity having the characteristic dimensions shown in Fig. 1 a frequency variation from 100 to 200 MHz is obtained when the gap is changed from 2 to 17 mm.

The characteristic impedance of the cavity, defined as the shunt resistance divided by the Q-factor, is about 60 Ω, typically, for the cavity in the large machine and about 40 Ω at the top frequency for the booster cavity. The first figure is an estimate, which can be made fairly reliably in this case, the latter figure has been measured with a model cavity. Q-factors of 10^4 and higher can readily be obtained with this type of cavity at 200 MHz. The values for speed, acceleration, and force to which the tuning plunger is exposed are found to be comfortably small in the large machine and acceptable in the booster, at least up to repetition rates of 25 to 30 Hz.

However, the maximum rate of change of frequency which the system is able to track is limited by the response of the servo system which, in turn, is almost entirely determined by the properties of the electro-mechanical transducer. With the help of a few simplifying but justifiable assumptions about the properties of the servo system, one finds that the dynamic tuning error, δf, of the cavity, resulting from the fact that the input frequency, f, is rapidly changing at the rate $\dot{f}$, is given approximately by

$$\delta f \sim \frac{\dot{f}}{\omega_c}\,, \qquad (2)$$

where ω_c is the angular cut-off frequency of the servo system, defined as the modulation frequency where the loop gain drops to unity.

If one requires that the fractional tuning error must not exceed half the inverse Q-factor of the cavity, one finds, remembering that $\dot{f}/f=\dot{\beta}/\beta$ (where β is the particle speed over the speed of light) that one must keep

$$Q \leqslant \frac{\omega_c \beta}{2\dot{\beta}}\,. \qquad (3)$$

Since it is possible to reduce the tuning error below the value given by eq. (2) by means of a preregulation of the servo system, somewhat higher Q-factors than those given by the condition (3) can be achieved. Nevertheless, it is clear that ω_c should be made as high as possible. It is limited, however, by mechanical resonances in the tuning plunger.

In order to study this question, and to get acquainted with some of the technological problems involved, two low power models containing servo systems have been build so far. An early model was built and tested at the Lawrence Radiation Laboratory at Berkeley and has been described in an internal report [2]. It differed from the design shown in Fig. 1 in as much as the tuner was built into the side of the resonator. More recently a model corresponding to Fig. 1 in size and construction has been built at CERN and work on this model is still in progress. The model is full scale, its dimensions correspond to the application in the booster but most results are applicable to the large machine as well.

A few details of this model may be reported here. The tuning plunger, including the part carrying the drive coil, is made of aluminium, 0.5 mm thick everywhere. The lower, cylindrical part of the plunger is fitted with axial slots to reduce eddy currents. It carries the drive coil of 1.5 mm anodized aluminium wire. The mass of the entire moving part is 200 g. It is suspended by a flexible system of 0.3 mm steel wires and springs. The RF current is carried to the outer conductor of the resonator across the capacity between the cylindrical part of the plunger and the surrounding tube (0.5 mm spacing).

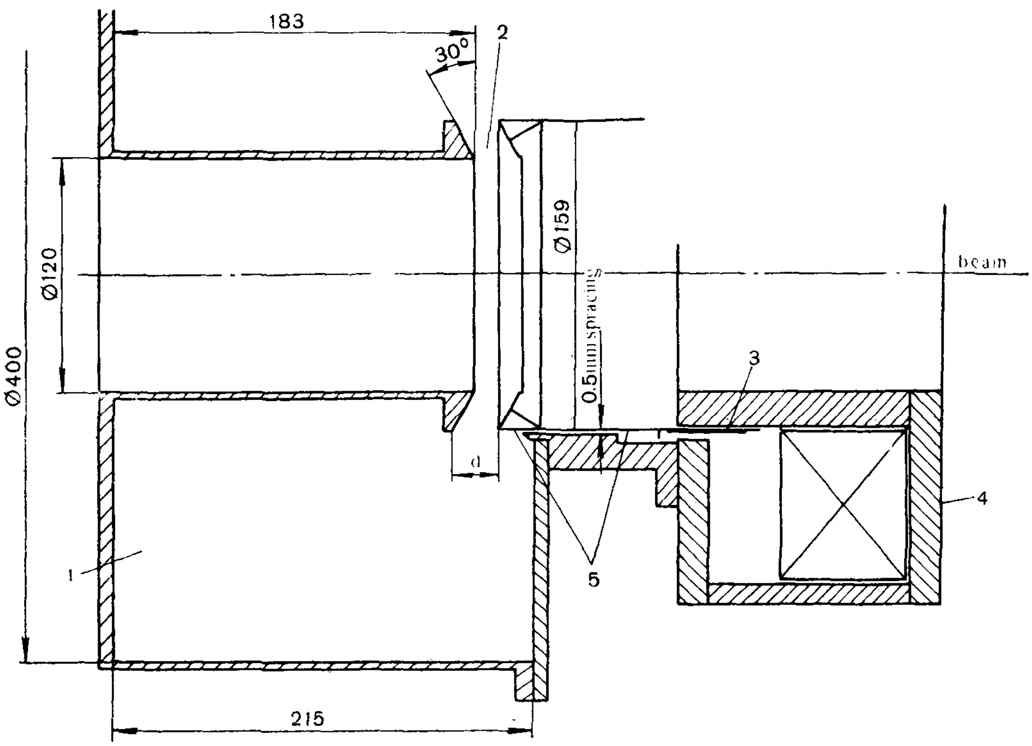

Fig. 1. Mechanically tuned cavity:
1 — cavity; *2* — accelerating gap; *3* — drive coil; *4* — dc magnet; *5* — tuning plunger (0.5 mm thick alum.).

At present, i. e. with the arrangement sketched in Fig. 1, the resonant frequency of the lowest mode of mechanical vibration of the tuning plunger occurs at 6.6 kHz. By inserting appropriate correcting networks into the servo amplifier one obtains a cut-off frequency f_c of about 3 kHz (similar results had been obtained with the Berkeley model, but with a smaller tuning plunger). The model is able to track a two to one frequency swing and a maximum rate of change of frequency which corresponds closely to eq. (3).

3. RF PARAMETERS FOR THE LARGE MACHINE

A short list of possible RF parameters for a 300 GeV machine [1] with an injection energy at, or above 3 GeV is shown in Table 1.

Table 1

Maximum rate of change of field	15 kGs/s
Peak RF voltage per turn	19 MV
Accelerating frequency	200 MHz
Harmonic number	5000
Number of RF cavities	144
Cavity Q	10^4
Cavity shunt impedance	0.6 MΩ
Maximum total RF power loss	2.1 MW
Total length of accelerating structure	87 m
Beam power with 10^{13} particles per pulse	0.5 MW

The proposed figure for cavity shunt impedance is more difficult to obtain at 3 GeV than of the higher injection energies. Indeed, if the full rate of rise of the magnetic field were applied at an injection energy of 3 GeV, the rate of change of frequency would be so large that the cavity-Q would be limited by the condition (3) to a lower value. However, it is planned to use a magnet cycle with a «front porch», i. e. a period of reduced rate of rise after injection, such that a Q-factor of about 10^4 is permissible.

Since $\dot{\beta}$ decreases with the inverse cube of the total injection energy, the situation improves rapidly for higher injection energies. At 6 GeV for instance, the cavity Q-factor is not limited at all by the condition (3) but it is the maximum value that one is certain to obtain from a copper cavity of the given construction and size. In this respect, the assumed value of 10^4 contains a large margin of safety. Injection energies substantially below 3 GeV, on the other hand, could not be accomodated without a large increase in RF power. As to the choice frequency, the following comments can be made:

A lower frequency would lead to a lower shunt impedance per unit length, not only because the cavities would become larger but also because the size of the tuner would have to be increased, which would lead to a lower cut-off frequency of the servo system.

A larger frequency — i. e. a larger harmonic number h — would tend to make the obtainable momentum acceptance too low and the phase oscillation frequency at injection too high. These two quantities are related by the equation

$$Q_s = \frac{hk}{\gamma_i^2} \frac{\Delta p}{p}, \tag{4}$$

where Q_s is the ratio of phase oscillation frequency to revolution frequency, $\pm \Delta p/p$ is the accepted momentum spread, and k is a numerical factor which depends on the stable phase angle (k is one half for a stationary bucket). It is assumed here that the transition energy is far above injection.

At 3 GeV, one is already forced to reduce the accelerating voltage at injection (making use of the front porch again) in order to reduce Q_s below one quarter. This leads to $\Delta p/p = \pm 1.3 \times 10^{-3}$ which is just acceptable. Since it follows from calculations done by Boilen [3] and, more recently, by Symon [4] that the RF bucket is already severely perturbed and its area reduced at $Q_s = 1/4$ if the particles receive only one accelerating kick per revolution, it becomes necessary to distribute the accelerating stations equally around the circumference of the machine.

If the injection energy is raised to 6 GeV, these limitations are almost completely removed and it becomes possible to put all accelerating cavities into only two long straight sections. It goes without saying, that this means a significant improvement, alleviating or avoiding many problems of phasing, remote controlling, power distribution and maintenance.

It may be noted in passing that eq. (4) furnishes another argument why injection energies below 3 GeV are almost excluded for an RF system like the one proposed, which has to work at a high frequency in order to be efficient.

4. RF PARAMETERS FOR THE BOOSTER INJECTOR

A list of possible RF parameters, based on mechanically tuned cavities, is given in Table 2 for a typical 6 GeV booster.

Table 2

Average radius	80 m
Repetition frequency	25 Hz
Maximum voltage per turn	1.67 MV
Harmonic number	336
Max.accelerating frequency (at $\beta=1$)	200 MHz
Number of RF cavities	120
Cavity Q factor	220
Cavity shunt impedance (at max.frequency)	8.9 kΩ
Maximum total RF power loss	1.3 MW
Total length of accelerating structure	60 m

Here, one relies heavily on the fact that the booster magnet excitation is sinusoidal.

Firstly, the acceleration voltage can be made proportional to the rate of change of field, $\dot{B}$, except for short periods just after injection and just before ejection, where a finite voltage is required — although $\dot{B}$ is zero — in order to keep an RF bucket of finite size. Thus, maximum accelerating voltage is only required when the frequency has almost reached its maximum and the gap across the tuning capacitor is large. At injection, when the gap is only 2 mm, the maximum voltage might lead to sparking.

Secondly, the maximum rate of change of frequency is greatly reduced by the fact that maximum $\dot{B}$ only occurs considerably above injection energy. In spite of this, the cavity Q-factor is severely limited by the condition (3) and heavy artificial damping must be applied, such that most of the RF power is not dissipated in the cavities but in the artificial load. Alternatively, one might use high-Q cavities and tolerate a large tuning error while $\dot{\beta}$ is large, keeping the voltage constant by a powerful automatic control system. This would lead to a low efficiency of the power amplifier and the power would be dissipated in the anodes of the final tube rather than in the load.

The maximum accelerating frequency is limited to about 200 MHz by the same factors that have been discussed in connection with the large machine. In eq. (4) h is lower because the booster has a smaller radius, but γ_t is also lower and the net result is about the same as for the 300 GeV machine at 3 GeV: if the RF voltage at injection is chosen such that the accepted momentum spread becomes $\Delta p/p = \pm 1.5 \times 10^{-3}$ one finds $Q_s = 0.17$. It can be seen that substantially higher harmonic numbers, resulting either from a larger booster radius or a larger frequency, would lead to difficulties.

When the mechanically tuned system is compared to a system of ferrite cavities [5] that occupies the same total straight section length, it is found that the total RF power consumption is almost the same in either case. However, the mechanical system has the advantage that its final frequency can be made equal to the injection frequency of the main machine. Thus, it becomes possible to synchronize both machines at the moment of beam transfer so that the bunches coming from the booster find themselves trapped in corresponding buckets in the large machine. This is considered to be an important advantage, since it is the only safe way of avoiding any loss of particles at this point. Among other advantages of the mechanical system one may mention again that the tuning power is very low, quite in contrast to the situation with a high repetition rate ferrite system.

REFERENCES

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DISCUSSION

I. Polk

What is the means of suspension of the moving element of the RF cavity?

W. Schnell

The tuning plunger is suspended by a system of 0.3 mm steel wires and springs. The restoring force of the suspension is small. The resonance frequency of the plunger and suspension system is below 10 Hz.

S. M. Rubchinskiĭ

How does Prof. Schnell propose to cope with the transient processes in the mechanical system?

W. Schnell

The servo system has a cut-off frequency of 3 kHz and the lowest resonance frequency of the piston is 6.5 kHz. The servo system is designed to have a good transient responce.